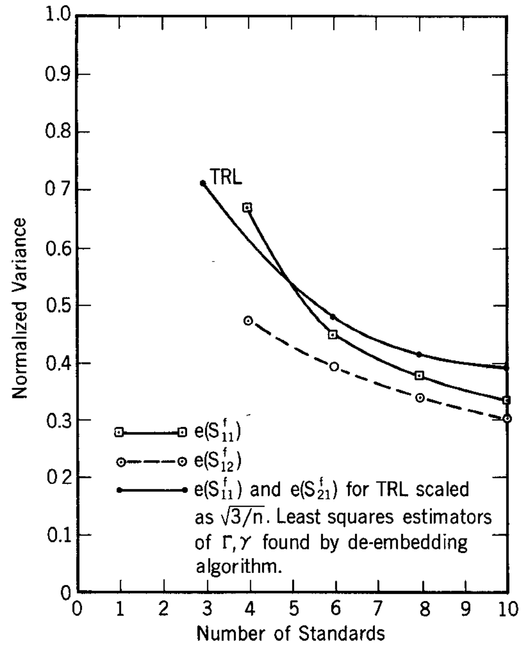

Fig. 7. The normalized variances of the untermination procedure are plotted as a function of the number of thru lines. The least-squares estimates of the propagation constant γ of the transmission lines and the reflection coefficient Γ_L of the offset loads are found during the untermination procedure.

tions is achieved by utilizing a large set of known reflective loads. When the propagation constant and the reflection coefficients of the standards are not known, then equal numbers of thru lines and reflective loads give the highest accuracy, although not as high as when the propagation constant and reflection coefficients are known. It was shown that the OSL technique was considerably less accurate than using sets of offset reflective loads.

The technique of unterminating illustrated here is very general and could be easily used to calibrate network analyzers. While the algorithm is computationally intensive, it may find application in practical situations because of its flexibility and accuracy. Furthermore, the variance of the data s^2 may be estimated from the residuals if more than three measurements are taken, allowing the variances of the least-squares estimates in the untermination procedure to be estimated. The variance of the de-embedded data could then be estimated as well.

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Microwave Radiometric Imaging at 3 GHz for the Exploration of Breast Tumors

B. BOCQUET, J. C. VAN DE VELDE, A. MAMOUNI, Y. LEROY, G. GIAUX, J. DELANNOY, AND D. DELVALEE

***Abstract*—A process of microwave radiometric imaging working at 3 GHz permits the mapping of radiometric intensities on a square area about half a decimeter on a side. These data, translated in terms of colored image, point out the existence of lateral temperature gradients in the tissues. This system was initially used in order to examine large breast tumors; at present, it is also used for the detection of smaller, impalpable tumors. We try to define the rules for the characterization of benignity or malignancy of small tumors which appear in a mammographic examination (X rays). The definition of an appropriate parameter, deduced from this image processing, seems to make it possible to indicate if the tumor is benign or malignant.**

I. Introduction

For several years, because women are more aware of breast lumps, more breast tumors have been discovered at an early stage. Therefore, new problems arise for differential diagnosis. Indeed, these tumors are often so small that they cannot be investigated with clinical examination. Because some of these lumps cannot be characterized by mammography or percutaneous cytology, it is often necessary to resort to surgery, although most of the lumps are not cancers. This is quite unsatisfactory since the cost is not negligible, no surgical procedure is harmless, and scars may change the breast structure enough to prevent early diagnosis of any future cancer, not to mention aesthetic and psychological problems. Therefore, a noninvasive method effective for tumor discrimination would be very welcome. For several years, microwave radiometric imaging has been used in an attempt to increase the reliability of diagnosis [1]–[12].

We have conceived an imaging process using a multiprobe radiometer which increases the number of measurements and improves their localization. We explain how this process is used now for the examination of tumors of the breast, in order to try to define the rules for the characterization of benignity or malignancy, mainly for situations where the usual screening process—mammography—has failed.

II. Materials and Method

The multiprobe radiometer [8], [9], working in the bandwidth 2.5–3.5 GHz, is made of a classical low-noise receiver with a gain of 50 dB and a noise factor of 5.5 dB. Consequently, its sensitivity is ±0.1°C. The multiprobe is a result of the juxtaposition of six open-ended apertures of rectangular waveguides

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B. Bocquet, J. C. van de Velde, A. Mamouni, and Y. Leroy are with the Centre Hyperfréquences et Semiconducteurs (UA 287 CNRS), Université des Sciences et Techniques de Lille Flandres Artois, 59655 Villeneuve d'Ascq Cedex, France.

G. Giaux is with the Centre de Lutte contre le Cancer, Rue F. Combemale, 59020 Lille, France, and the Centre Bourgogne, Lille, France.

J. Delannoy and D. Delvalee are with the Centre de Lutte contre de Cancer, Rue F. Combemale, 59020 Lille, France.

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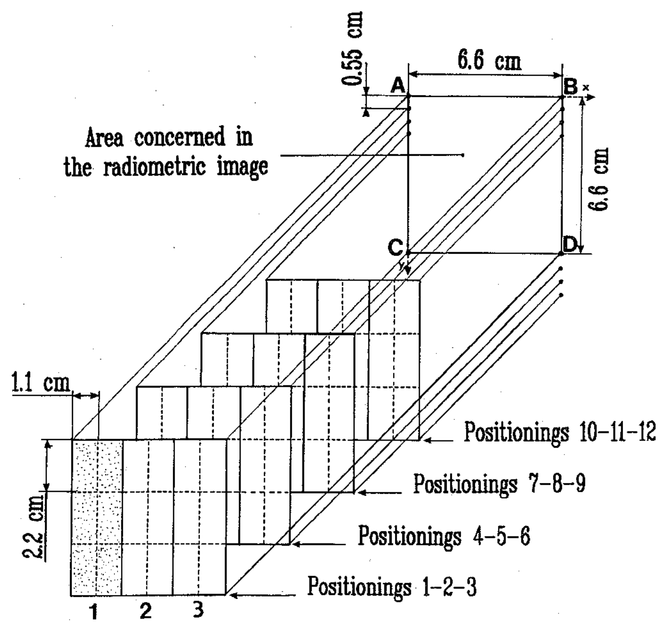

Fig. 1. Mode of positioning of the multiprobe leading to the acquisition of 72 radiometric data for an area of 6.6 cm × 6.6 cm. The dashed area corresponds to the first position of the multiprobe.

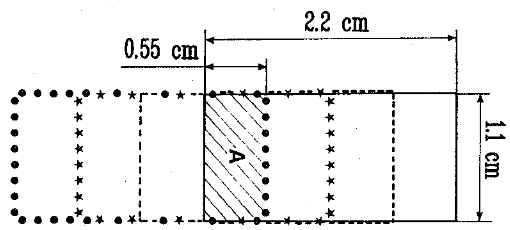

Fig. 2. Different positions of the probe aperture: ●●●● position 1; ★★★★ position 2; ----- position 3; ——— position 4.

filled with a low-loss dielectric ($\epsilon' = 25$). The radiometric system is conceived in such a way that the noise measurement is not affected by the emissivity effects resulting from a small mismatch at the probe–tissue interface [10]. In this way, in the case of living tissue, the radiometric intensities can be associated with a volume [11] located in front of the probe aperture for a depth of up to about 2 cm at the frequencies considered. The output signal is expressed in terms of an excess of radiometric temperature ΔTm (with respect to a reference temperature T_0). The system is completed by a microcomputer which manages the commutation of the probes, stores the radiometric data, and carries out an imaging synthesis according to the data processing which is described below.

The mode of positioning (Fig. 1) consists in 12 positionings of the multiprobe on an area of 6.6 cm × 6.6 cm. The data processing takes into account the overlapping of the elementary area covered by the probes, and the coupling between the probes and the lossy material [12].

We show (Fig. 2) how, for different positionings, the probes cover different parts of the area under investigation; we will affect the center of every such dashed area (point A in Fig. 2) with a radiometric temperature resulting from the corresponding four radiometric measurements. The weighting of these radiometric data refers to the knowledge of the near field

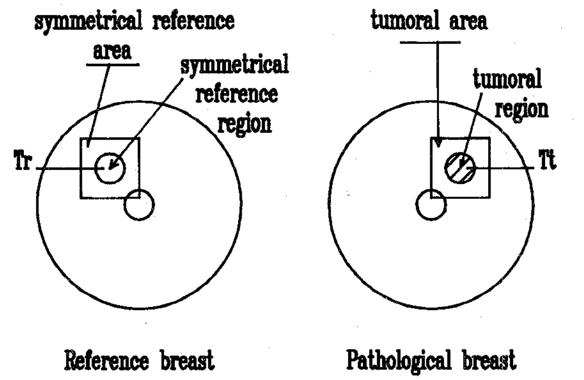

Fig. 3. Marking of the regions of breast under thermological investigation.

radiated by the probes in a lossy material such as living tissue [12].

Referring to Fig. 2, the radiometric excess of temperature at point A is evaluated by the following expression:

$$\Delta Tm_A = 0.125\Delta Tm_1 + 0.375\Delta Tm_2 + 0.375\Delta Tm_3 + 0.125\Delta Tm_4 \quad (1)$$

with ΔTm_i being the radiometric temperature measured by probe i ($i = 1$ to 4).

Having a matrix of values ΔTm_A corresponding to the different points A (Fig. 2) covering the area under investigation, the next step of the data processing consists of an interpolation between the different data. This process, in which the large sides of the probes are vertical (the "longitudinal mode" of positioning) is combined with a "transverse mode" of positioning, in which the large sides of the probe are horizontal. The data obtained lead to a 144 point radiometric image; a pixel is 5.5 mm × 5.5 mm. Consequently, our two-dimensional imaging process presents a spatial resolution which is surely better than other previous radiometric investigations. So far, studies made with this process on compact thermal structures [9], [11] in water have shown that the diameter D of a cylindrical structure ($\Delta T = 5°$, D between 1 and 4 cm) at a depth of up to 2 cm can be determined with an accuracy of ± 0.2 cm.

The exploration essentially leads to a method for characterizing the benignity or malignancy of tumor in a breast area where a clinical examination or mammography predicts a tumor, even if the lesion is not palpable.

These clinical evaluations are based on a comparison of two radiometric images. One is obtained on diseased tissue. The other concerns the symmetrical part of the body and provides a reference image. The multiprobe is maintained close to the skin temperature (generally 35°C) so as to avoid any modification of the tissue's temperature distribution by contact with the multiprobe. The patient lies on the table; thus the breast is relatively flattened. The thickness of the tissues under investigation is generally not greater than several centimeters, a condition compatible with radiometric investigations. The "tumoral region" is marked after clinical examination and mammographic study (Fig. 3). Then, a "reference region" is marked on the other breast (symmetrical region). Radiometric data are acquired on both the reference region and the tumoral region.

Examples of colored images cannot be presented here. Such images, obtained in the first step of this study, have been published in [9].

In the present step, we interpret the data by the determination of two parameters (Fig. 3):

$\Delta 1$—the difference of temperature between the warmest point image, Tt, of the tumoral region of the pathological breast and the temperature Tr of the symmetrical point image of the reference breast.

$\Delta 2$—the difference of temperature between the warmest point image and the coldest one of the set of the breast. This difference is determined by the upper and lower limits of the temperature scale.

From the data, we try to predict the malignancy or the benignity of these lesions. Use is made of the values of an empirical radiometric ratio R, defined by the relation

$$R = 100 \times \Delta 1 / \Delta 2. \quad (2)$$

III. Results

After preliminary experiments on random patients with breast tumors, the acquisition method and software were improved. The image resolution, 74 points at the very beginning, was improved to 144 points. After we had successfully recorded data from about 72 patients, the system seemed to be reliable enough to be used in more critical situations (i.e., very small or impalpable lesions detected by mammography).

We therefore selected new patients for whom it was impossible, by such standard investigations as clinical examination and mammography, to confirm either malignancy or benignity in a tumor. To avoid inflammation, which could change the thermal pattern within the breast, transcutaneous cytology was achieved whenever possible after microwave imaging.

Since it was impossible to achieve reliable diagnosis with standard diagnostic means, most of the patients had surgery guided with a dedicated needle inserted into the tumor under X-ray control (harpoon technique) [13]–[15]. Therefore, we were later able to compare our results with histological examinations.

For the first 18 new patients the crude evaluation technique previously described gave quite good results. Indeed, all the malignant lesions had a radiometric ratio greater than 65% while benign lesions were characterized by a smaller ratio than 55%. Unfortunately, further investigation on seven other patients did not give the same good correlation between the radiometric ratio and the histological characteristics of the tumor. In fact, it seems that we have to define a zone of uncertainty between 55% and 70%, where it is wise not to assert malignancy or benignity.

IV. Discussion

For very few investigations, the radiometric ratio is included within the zone of uncertainty. Nevertheless, it seems that, otherwise, we could discriminate between malignancy and benignity. Since for the lesions investigated no diagnosis could be made with existing techniques, the results are encouraging.

The diagnosis so far is based on the association of clinical, mammographic, and cytological examinations. Microwave radiometric imaging, combined with the other methods, may help us to increase the reliability of our diagnosis. Nevertheless, there are many problems to be solved. It is obvious that we have to improve the way we collect and analyze results. Indeed, for these small tumors, the temperature scale we have to measure is very narrow (generally from 0.5° to 1.5°C). Therefore, the noise is not negligible. The technology has to be improved. A new device, including one radiometer for each waveguide, is being built. This will decrease the acquisition time and increase the signal to noise ratio.

But the main problem is still the methodology. We do not yet know exactly where and what to measure and what is the actual correlation between thermogenesis and cancer. We also have to improve the way we analyze data in order to be able to extract a greater amount of information from radiometric images. We hope soon to be able to increase our success rate.

V. Conclusions

We have presented a microwave radiometric system working at 3 GHz that provides images for a square area about half a decimeter on a side. This process, evaluated in clinical explorations of breast cancer for very small, impalpable tumors, seems to be better than processes involving infrared thermography.

The relatively small number of cases in our population of patients implies that our conclusions must be taken as tentative at the moment. The preliminary results are promising. We are now carrying out our exploration of breast tumors on a larger population in order to reach a statistical comparison.

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